INVESTIGATION OF TECHNICAL PROBLEMS RELATED TO

DEPLOYMENT AND RETRIEVAL OF SPINNING SATELLITES

Summary Final Report on NASA Grant NGR 39-009-162

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ABSTRACT

Results of a three-year research effort at The Pennsylvania State University (NASA NGR 39-009-162) on retrieval and deployment problems associated with orbiting payloads are summarized. Answers to several basic questions about rendezvous, docking, and deployment dynamics and controls were obtained. A basic retrieval mission profile was formulated in order to develop relevant technology. A remotely controlled "retrieval package" was conceived. Special deployment dynamics problems associated with high altitude deployment were investigated, and new knowledge of payload spin reorientation was obtained. These efforts have been documented in several reports and publications.

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1. INTRODUCTION

NASA Grant NGR 39-009-162 was awarded on January 1, 1970 for the purpose of studying orbital retrieval technology associated with spinning uncooperative objects. The initial grant expired on December 31, 1971 and was renewed for one year with objectives expanded to include certain payload deployment problems. Final expiration occurred on December 31, 1972. Answers to several basic questions related to rendezvous, docking, and deployment dynamics and controls were obtained. Specific problem areas were identified, and mission requirements and constraints were formulated for the purpose of developing operational sequences and conceptual spacecraft designs. Work has been well documented, and associated publications are listed in Section 3. For detailed technical discussions refer to these documents.

Areas considered include the problem of despinning an arbitrary spinning object of moderate size, automatic orbit control for maintaining the shuttle orbiter at a given parking position relative to an object, transfer trajectories of a despin package, techniques for determining spin axis and rate of an uncooperative body, and high altitude deployment and reorientation of a payload. A basic retrieval mission profile had to be formulated in order to develop relevant technology. Mission requirements and constraints led to a remotely controlled package for capture and despin of such objects. The "retrieval package" concept is described below.

In another phase of this study a technique applicable to satellite deployment into high circular orbits was investigated. The apogee motor assembly with paired satellites (AMAPS) technique takes advantage of an attitude instability of spinning bodies to deploy pairs of satellites into these high orbits from a low orbiting space shuttle without using an orbit-to-orbit tug. A freely spinning body with energy dissipation is

stable only when rotating about its major principal axis. The complete payload is deployed from the shuttle as a package which includes satellites, solid rocket motors, and required electronics. The concept is described briefly in the next section. Sequential events include deployment from the shuttle cargo bay, initial spin up by a deploy/retrieve package, injection into apogee transfer by a solid rocket motor, separation and spin axis transfer initiation, transfer to apogee, and apogee injection with subsequent separation and positioning of the two satellites. Recent activities in this area included the investigation of final spin direction control, i.e., elimination of ambiguity in apogee motor pointing direction.

Several graduate students have participated in this work. To date, three master of science theses have been written on the study problems and solutions. Three other theses in this area are still being completed.

2. SUMMARY OF TECHNICAL ACHIEVEMENTS

Many of the 2700 objects orbiting Earth possess angular momentum in the form of steady spin or tumbling because of stabilization mode, attitude jet failure, collision, etc. Given enough time, tumbling motion will always dissipate to steady spin due to energy absorption resulting from structural flexibility, propellant sloshing, and nutation dampers. A significant problem arising in missions dealing with passive objects such as satellites and disabled space bases is docking with a target which possesses angular momentum. Thus, in the case of a discarded satellite, steady spin can be expected if angular momentum is present.

A considerable amount of information is available in the literature on handling passive, non-spinning objects. Limited work has been done with capturing targets of moderate size using a modified Apollo command and service module. Thus, properties of bodies possessing angular momentum are well known, but promising capture and control techniques for spinning objects have not previously been studied in depth. The work summarized here deals primarily with docking problems associated with this situation.

Operational Considerations

Since the most economical means of reaching an object in a low orbit for retrieval, repair, or elimination will be by using the space shuttle, many aspects of the operational sequence assume a man will be controlling the events and maneuvers. Automatic control systems are assumed whenever practical, but the nature of such missions requires the ability of a man to make decisions and perform functions which are prohibitive in an automated mode because of the inherent uncertainties involved. Missions to high altitude orbits would require very similar maneuvers. However, shuttle performance is expected to limit it to low altitude orbital missions and an orbit-to-orbit vehicle may also be required for high altitude retrieval.

The initial task in a retrieval sequence is considered to be locating and identifying the object upon arrival in its predetermined vicinity. The size and shape of the search area will greatly influence the method of search and identification, and time to search. Furthermore, a successful rendezvous requires extreme accuracy in orbit determination. A non-cooperative radar rendezvous system is considered to be available using current technology. It is understood that the accuracy of orbit determination by ground tracking will permit the shuttle to be guided very close to the target object.

In fact, the search region within which the target is predicted to be located is assumed to be a cone with a 4 mile (6.4 km) diameter, 5 miles (8 km) long (1σ), up to a possible 12 mile (19.3 km) diameter, 15 miles (24 km) long (3σ), with the shuttle at the apex. A non-cooperative radar rendezvous should have a system range of at least 35 miles (56 km) with range accuracy of about 1 percent and angular accuracy of 2 milliradians (3σ). Once in the search cone the system can automatically scan the region and should detect an object within minutes (Publication 3, Appendix C).

One possible method of identification upon initial acquisition of an object employs a television camera guided by the radar tracking system. A zoom lens can be used to receive an image with limited resolution. If the object is spinning a "frozen" scene television display can be produced. This is equivalent to using an electronic strobe, except the picture is "flashed" on a storage tube. The image can be held or reinforced at the spin rate of the object. However, the degree of resolution is somewhat uncertain with such a system. To determine the dynamic state and physical condition of a spinning body with assured accuracy and image quality, an optical or electronic strobe is very effective once the shuttle is within a few hundred feet of the target (Publication 7).

After locating and identifying the object, orbital maneuvers are executed to approach and acquire a stand-off position relative to the target. If the object is not spinning or has some minimal spin rate and is of acceptable size, a direct docking may be attempted. Otherwise, the shuttle must maintain a stand-off or parking position while the retrieval package is deployed to eliminate angular momentum and capture the target. Objects which are too large for retrieval are not considered reusable. In many cases it is desirable to simply eliminate such large pieces of "space junk"

from orbit. To accomplish this a remotely fired retro-pack could be attached to an object after despinning. Of course, this device would reenter with the object and would not be reusable. Furthermore, large objects, such as empty upper stages and payload fairings, in low orbits decay rapidly due to pronounced drag effects.

Standard rendezvous maneuvers are anticipated during approach of the shuttle to the stand-off position. Upon arriving at this position an autopilot will be enlisted to maintain spatial relationship with the target while the attitude control system maintains required orientation. Figure 1 illustrates one possible situation in which the shuttle is positioned along the orbital path of the object. Assuming a despin maneuver is required, the retrieval package must make an orbital transfer from the shuttle to the position of the target such that the axis of this remotely controlled spacecraft is in line with that of the object spin axis. Fine adjustments are to be made after one of the shuttle crewmen checks alignment via a remote bifocal television system on the package. This terminal situation is represented in Figure 2, illustrating the retrieval of OSO 1.

Position of the shuttle and transfer trajectory of the retrieval package during capture operations are very important factors to mission success. An artificial reference frame must be provided the crew in order to remotely perform capture maneuvers and satisfy viewing constraints for continuous communications and observations. In terms of propellant require- ments of the shuttle to maintain such a position, the ideal location would be along the orbital path of the target, as shown in Figure 1. Propellant expenditure would be for correcting perturbations only. Excessive fuel would be required to maintain an out-of-plane position; thus, it is assumed that the shuttle will be coplanar with the target during retrieval maneuvers.
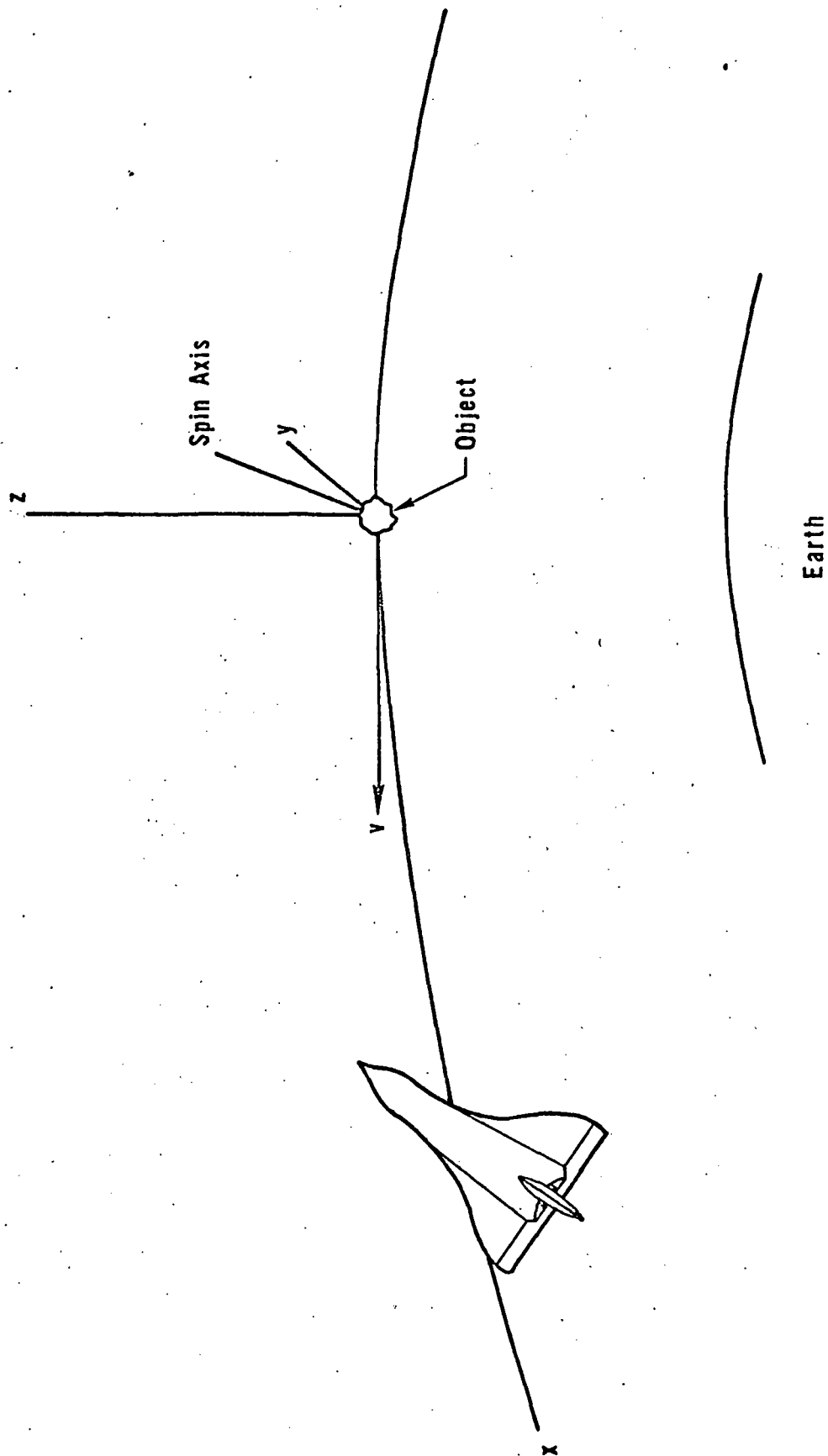
Figure 1 Shuttle/Object Relative Position Nomenclature
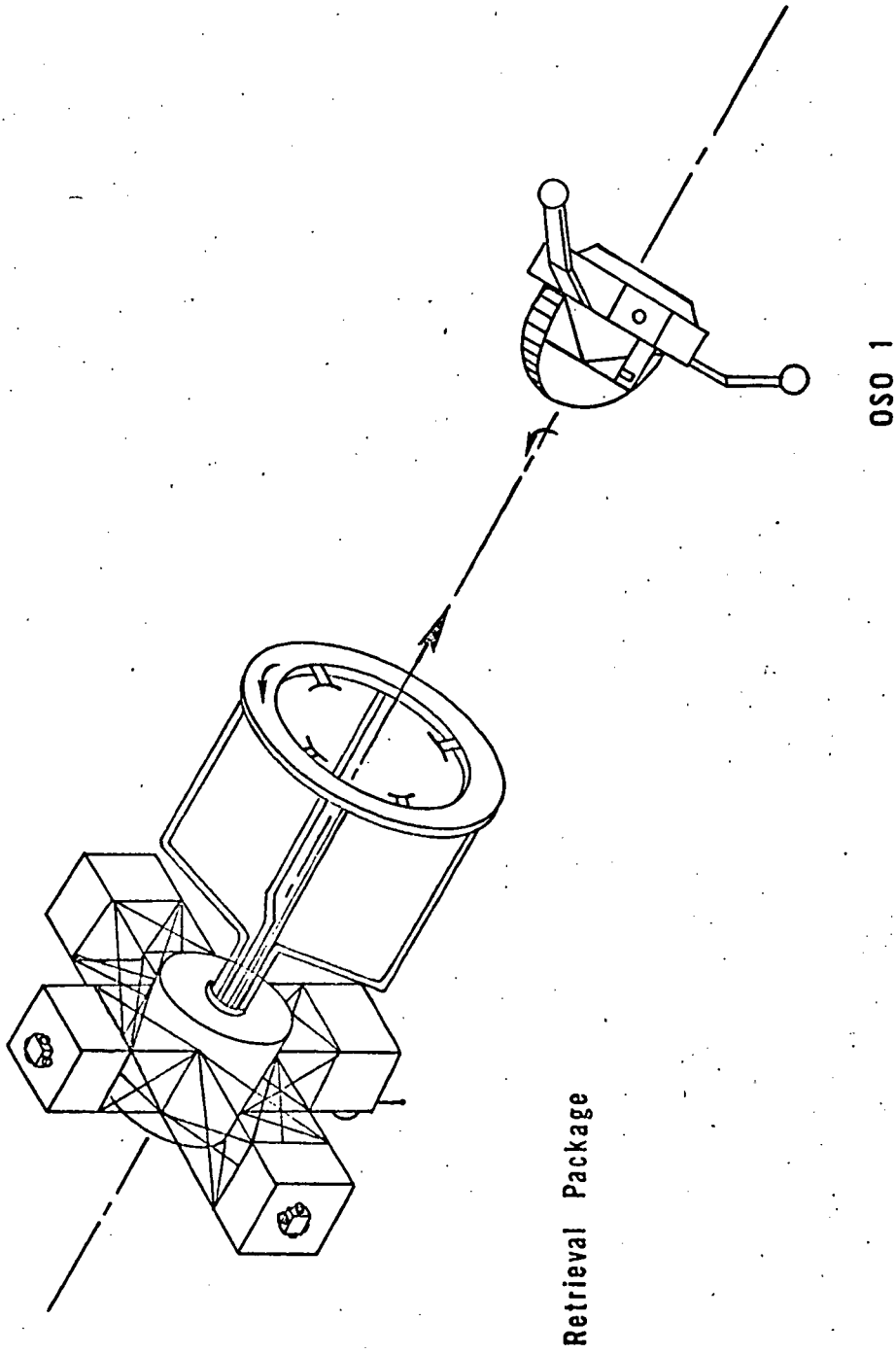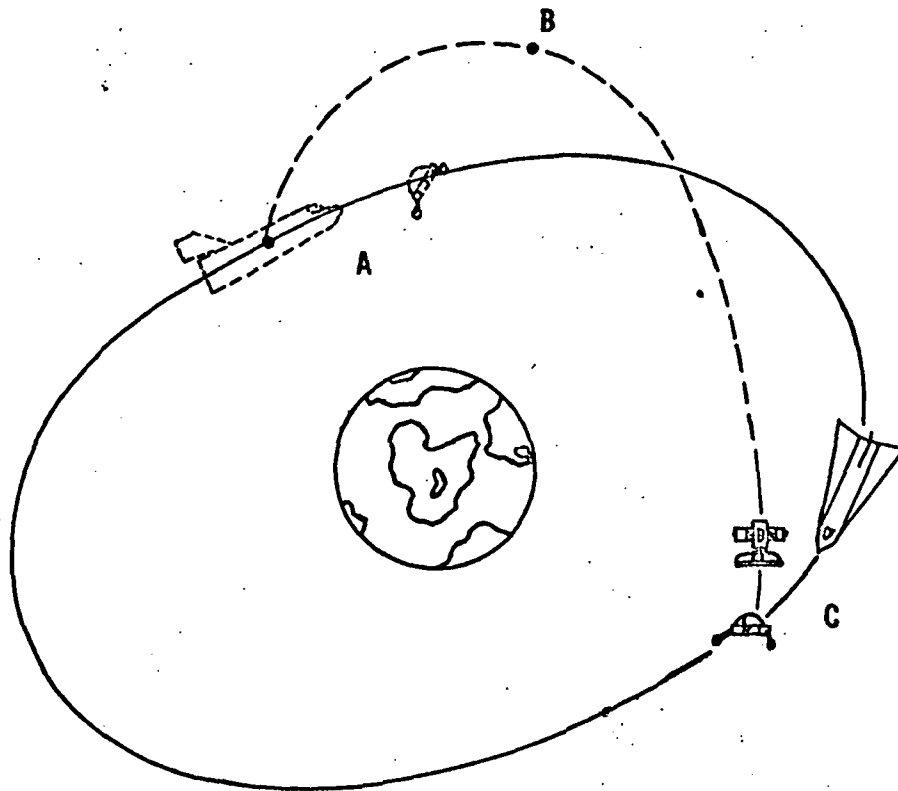
Retrieval Package

OSO 1

Figure 2 Retrieval Package Aligned with Spin Axis of OSO 1

Final selection of a stand-off position for a given situation will depend on spin axis orientation of the target with respect to the orbital plane.

The transfer trajectory of the retrieval package to the target will, in turn, depend on shuttle position and object spin orientation.[11] In general, this spin axis will not lie in the orbital plane of motion. Therefore, an out-of-plane transfer must be assumed for proper terminal alignment. A minimum of three thrust impulses is required for a transfer time of less than half an orbital period. If the shuttle is maintained along the orbital path of the target, then initial and final transfer conditions on orbital energy and altitude are identical, but a change in orbital position relative to the object has taken place. A typical transfer sequence is illustrated in Figure 3. At point A the package leaves the orbital plane on a path corresponding to an orbit with a different period. A midcourse thrust at B is necessary to bring the package back to the original plane in less than half a period. The final impulse at C will stop the package, and terminal capture procedures may then commence.

Actual attachment to and despin of the object is carried out by a ring which is aligned with the object spin axis. This ring is spun up to the same angular speed as the target, while the main body of the despin package remains 3-axis oriented in an inertial frame as shown in Figure 2. After the ring is synchronized through the use of an axially mounted television camera, the entire spacecraft is translated along its axis until the ring-plane reaches a position near the center of mass of the object. At that point attachment arms are extended from the ring toward its center. Once the target is secured by these arms, despin is executed while momentum is dumped via attitude jets on the main body of

Impulse sequence:

A — Initial impulse geometry

B — Midcourse correction

C — Terminal impulse geometry

Figure 3 Typical Three Impulse Transfer Geometry for Retrieval Package

the package. A docking device on this inertially oriented body allows the shuttle to rendezvous and recapture the package with object in hand, and stow it in the cargo bay for return or repair.

Retrieval Package

The problem of despinning an uncooperative object has been cited as one of primary interest in this study. The decision to propose a separate device for this operation is the result of safety and performance considerations with respect to the shuttle. With a despin package maneuvering about the object at a "safe" distance away from a manned vehicle, the risk of bodily harm from a mishap is minimized. Crewmen on the shuttle can maneuver a small spacecraft with great ease, especially when aligning the package with the target spin axis (Publications 4, 5 and 7).

The despin package is conceived to consist of two major components; tender and despin ring. The tender provides all functions required for orbital transfer and alignment with the target, while the despin ring performs the actual capture of the object. A configuration based on constraints and mission objectives were formulated. The complete space-craft is illustrated in Figure 2, with tender and despin ring shown in greater detail in Figure 4. Overall size of the despin package is limited by the shuttle cargo bay dimensions, proposed to be 15 feet (4.6 m) in diameter and 60 feet (18.3 m) long. This restricts the ring size and, in turn, limits the size of objects which can be considered for retrieval. The tender is configured to allow maximum applied torque from the reaction control system while permitting large values of inertia about the ring axis. These innovations will minimize propellant requirements and effects of disturbances associated with the despin sequence. Thus,
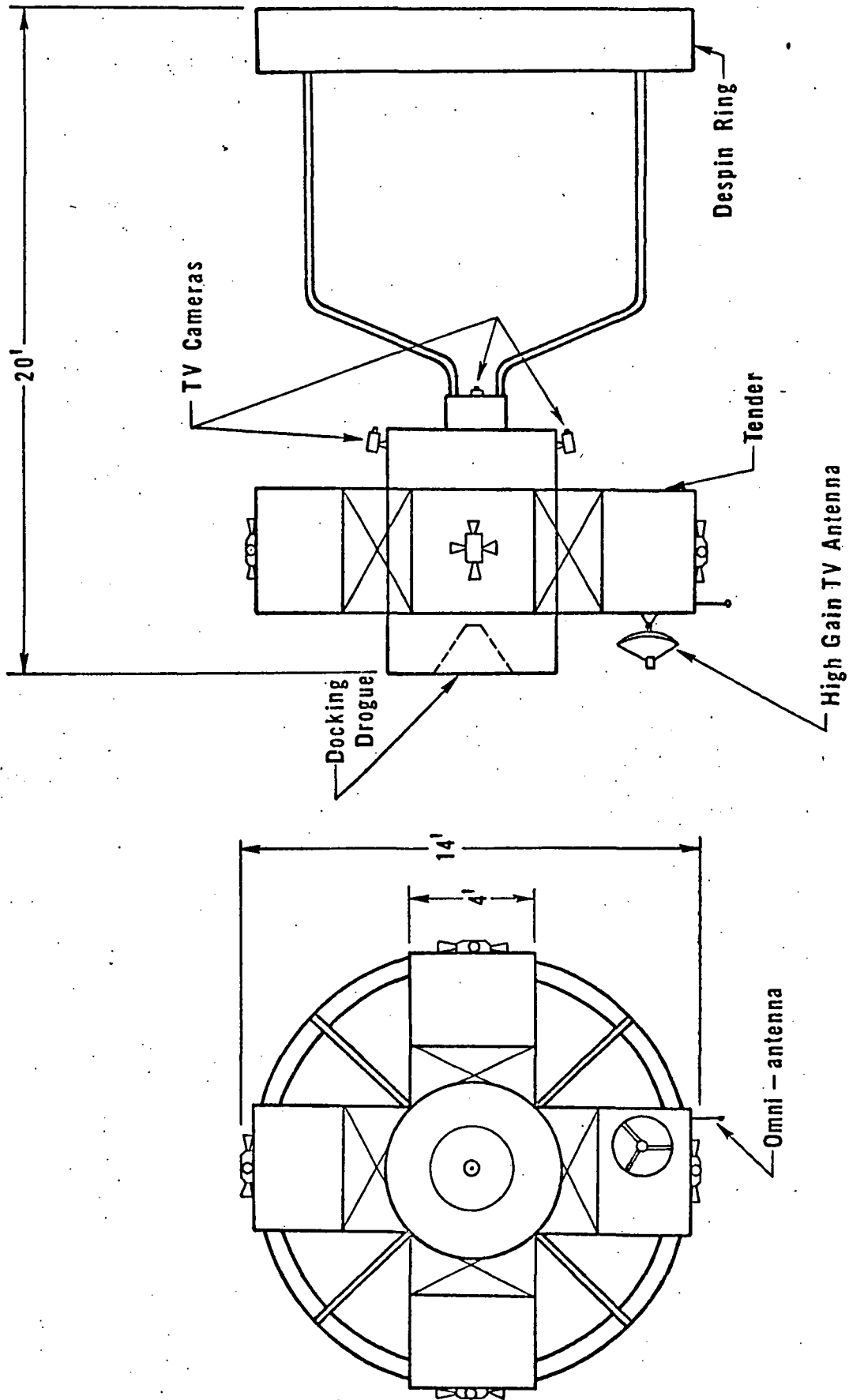
Figure 4 Details of Retrieval Package Configuration

the major dimensions of this main body were selected as 14 x 14 x 8 feet (4.3) x 4.3 x 2.4 m). Compartments in the four arms contain the power system, monopropellant reaction control equipment, and command and telemetry system. The central cylinder houses the ring spin motor, twin-gyro controllers for the attitude control system, a reserve propellant tank, and shuttle docking drogue. The despin ring as conceived here has an inner diameter of 13 feet (3.9 m) and an outer diameter of 14 feet (4.3 m). The four docking arms are assumed to extend inward another foot (0.3 m) when in the retracted position. These arms are independently operated to permit capture of arbitrarily shaped objects and can each extend to 6 feet (1.8 m) in length. Therefore, objects as small as one foot (0.3 m) and as large as 11 feet (3.3 m) in diameter can be handled by the same despin ring. Structural support of this ring is provided by four struts illustrated in Figures 2 and 4.

Attitude and orbit control systems, in conjunction with remote commands from the shuttle, provide maintenance of position and orientation during transfer and docking. Twin-gyro controllers were chosen for momentum exchange and monopropellant reaction jets for momentum dumping. Since the tender is inertially oriented in the attitude maintenance mode there is no first-order cross-coupling. A momentum wheel could be used during ring spin-up and despin to conserve propellant. However, this would introduce more complexity into the system. Furthermore, the reaction jet tanks are easily refillable before each retrieval sequence. This reaction control system also provides thrust impulses for transfer to the target and aligns the package with the target spin axis under commands from the crew. Once the package is aligned, capture should be accomplished in a short period of time. Therefore, relative position drift is very slight during this time interval, and an automated position control system is not required.

The command and telemetry system incorporates television cameras and two antennas, an extendable omnidirectional type for the command and telemetry link, and a high gain directional dish for television transmission. The high gain dish imposes some constraint on the shuttle stand-off position in order to satisfy the viewing requirements for this antenna. One camera is mounted along the ring axis at the center of the support struts, and spins with the ring. This offers a very convenient means of synchronizing ring and target spin rates and provides a check on final alignment. Two other television cameras mounted diametrically opposed on the central cylinder are used for relative position maintenance through bifocal viewing of the target. These cameras will be focused at a given distance from the target which will permit rough alignment and stand-off parking simultaneously. When the angle between the spin axis and the center line of the despin ring is zero, the axes will be aligned. Slight spin desynchronization will cause an apparent rotation of the target about its actual spin axis with frequency equal to the difference between object and ring spin rates. This can be used to make fine adjustments for final synchronization. The despin sequence may then proceed.

The shuttle/package docking apparatus, shown in Figure 5, consists of a folding arm mechanism with probe, docking latches, and tender drogue. The folding arm extends a docking probe to a position which is easily observable by the pilot. The shuttle then maneuvers to the retrieval package, and upon completion of docking, it is deactivated and retracted into the cargo bay.

High Altitude Deployment Study

A spinning semi-rigid body, free of applied torques and active controls is stable only when rotating about its axis of maximum moment of inertia.
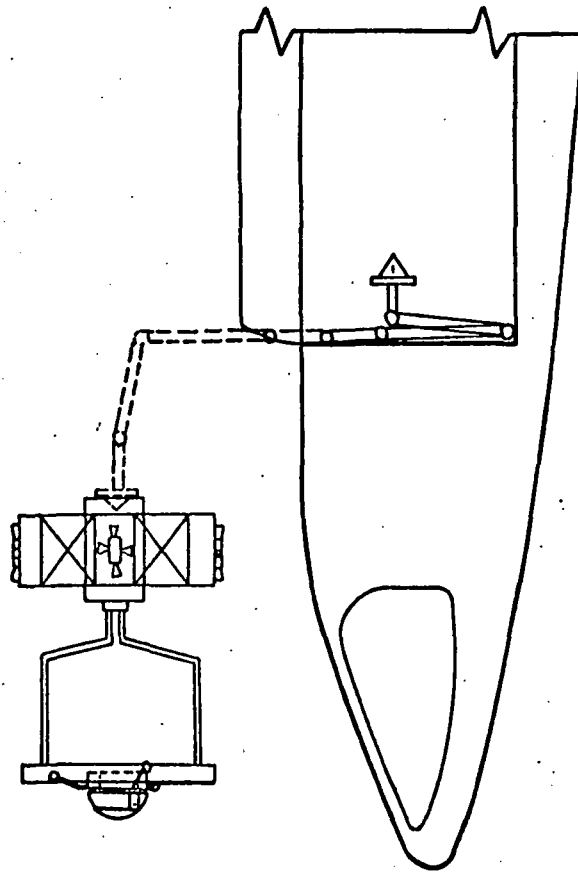
Figure 5 Shuttle/Retrieval Package Docking Arrangement

This phenomenon has been widely used advantageously for passive attitude control of earth satellites, but has proven disastrous to those who have ignored it. Explorer I is a classic example of the consequences of such a neglect. After only a few hours into the flight of the first American satellite, radio signals indicated a tumbling motion had developed and was increasing in amplitude in an unstable manner. It was concluded that the four turnstile wire antennae were dissipating energy; thus, causing a transfer of body spin axis from the axis of minimum moment of inertia to a transverse axis. The Apogee Motor Assembly with Paired Satellites (AMAPS) technique uses this instability to passively transform spin axis orientation during deployment of a pair of satellites into high circular orbits from either a low-orbiting space shuttle or a launch vehicle which performs the apogee transfer injection. The use of this technique with a surface-to-orbit shuttle system would eliminate the requirement for an orbit-to-orbit tug; thus, permitting the use of relatively simple deployment hardware. Active attitude control beyond apogee transfer injection is not required when the AMAPS scheme is used with a launch vehicle or shuttle. Furthermore, the requirement for built-in apogee kick motors as part of the satellites is eliminated (Publications 8 and 10).

Primary objectives of this study were to develop the AMAPS scheme and investigate methods for analytically determining spin axis transfer times and controlling final spin orientation for realistic satellite configurations. Energy dissipation is provided by a viscous ring damper mounted on the major axis. Solutions of attitude motion for large-angle reorientation of asymmetric spacecraft are not generally available and were obtained by numerical methods. When the axis of maximum moment of inertia is oriented close to the angular momentum direction, linearization is possible and results are available in the literature for such cases.

There are two basic configurations with which the AMAPS technique may be associated. When used with a launch vehicle no apogee transfer injection motor is required. Such a scheme is illustrated in Figure 1. Either the upper stage of the booster is spin stabilized, or a spin table is used to spin-up AMAPS about the YY-axis. Immediately after injection into a high altitude transfer orbit the payload attitude is changed so that the momentum vector is reoriented for later apogee firings, and then the release sequence is executed. Since the assembly is stable about its axis of maximum moment of inertia, energy dissipation would result in the transfer of spin to the axis of maximum moment of inertia while keeping the direction of the angular momentum vector fixed in inertial space. It is assumed that the ZZ-axis is the body axis of maximum moment of inertia and YY is the axis of minimum moment of inertia. The ZZ-axis will tend to align itself with the angular momentum direction if the YY-axis is initially perturbed when separated from the launch vehicle, and the assembly has an energy absorber or nutation damper. Figure 6 shows how initial conditions can be achieved in order to start the transfer of the rotation axis as the assembly leaves the launch vehicle. Immediately after injection into apogee transfer by the upper stage, a pin puller device is fired. This allows a spring to start rotational motion about the XX-axis, which induces a perturbation, starting the transfer of rotation axes. When the split hinges line up with the axle flats, springs will push the assembly away from the upper stage, and the payload is then freely precessing. The axially mounted damper shown in Figure 6 will absorb energy in such a way as to transform spin axes. The rate of axis transfer for a given payload is a function of initial spin rate and the energy dissipator configuration. When the assembly has stabilized and is rotating only about the ZZ-axis,
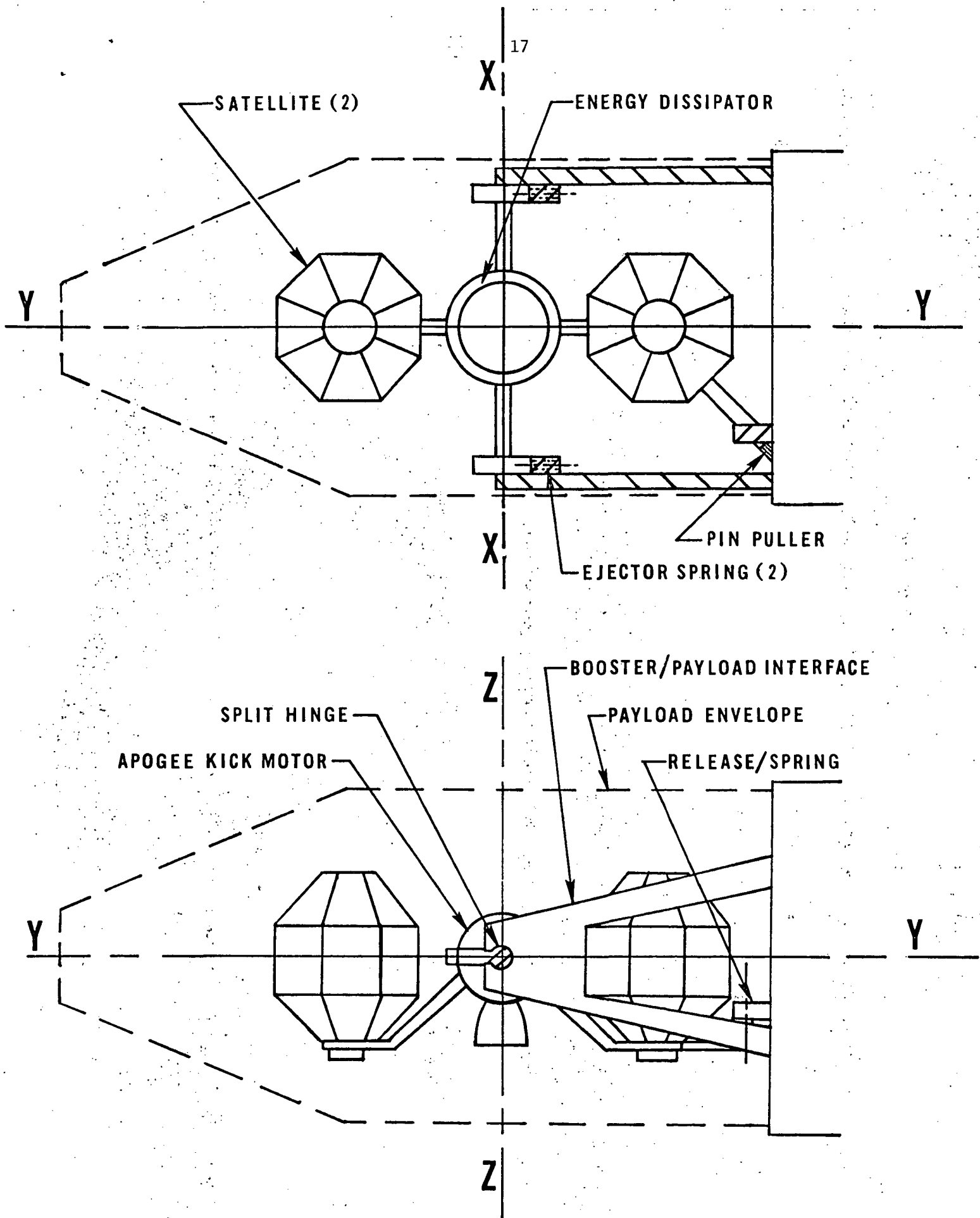
Figure 6. AMAPS Configuration for Launch
Vehicle Applications

then this axis will be parallel to the original YY-direction, and the assembly will be in the proper orientation for apogee firing. After apogee kick the two satellites can be separated and, if desired, spun-up simultaneously by converting angular momentum of the assembly to the satellites. Spin rate adjustments and positioning around the orbit can be done with individual satellite propulsion systems.

The other basic configuration useful with the AMAPS technique is associated with deployment from a low-orbiting space shuttle. This scheme is illustrated in Figure 7. The payload package consists of two satellites, an apogee kick motor, and an apogee transfer injection motor. This assembly is deployed from the cargo bay and spun up about the Y-axis by a deploy/ retrieve device. The payload package is then separated from this device, and the apogee transfer motor is fired shortly thereafter. This is followed by reorientation with the limited attitude control capability of the injection motor subsystem, and then payload separation and perturbation occur. The apogee transfer and axis transformation sequence is shown schematically in Figure 8.

In conjunction with the AMAPS technique an investigation of final spin direction of the payload package was carried out.[12] Proper alignment of the apogee kick motor is critical and uncontrolled reorientation may result in a 180° pointing direction error. To eliminate this possibility the feasibility of controlling this ambiguity was studied. Results indicate the proper pointing direction can be guaranteed through a simple device (Publication 12).
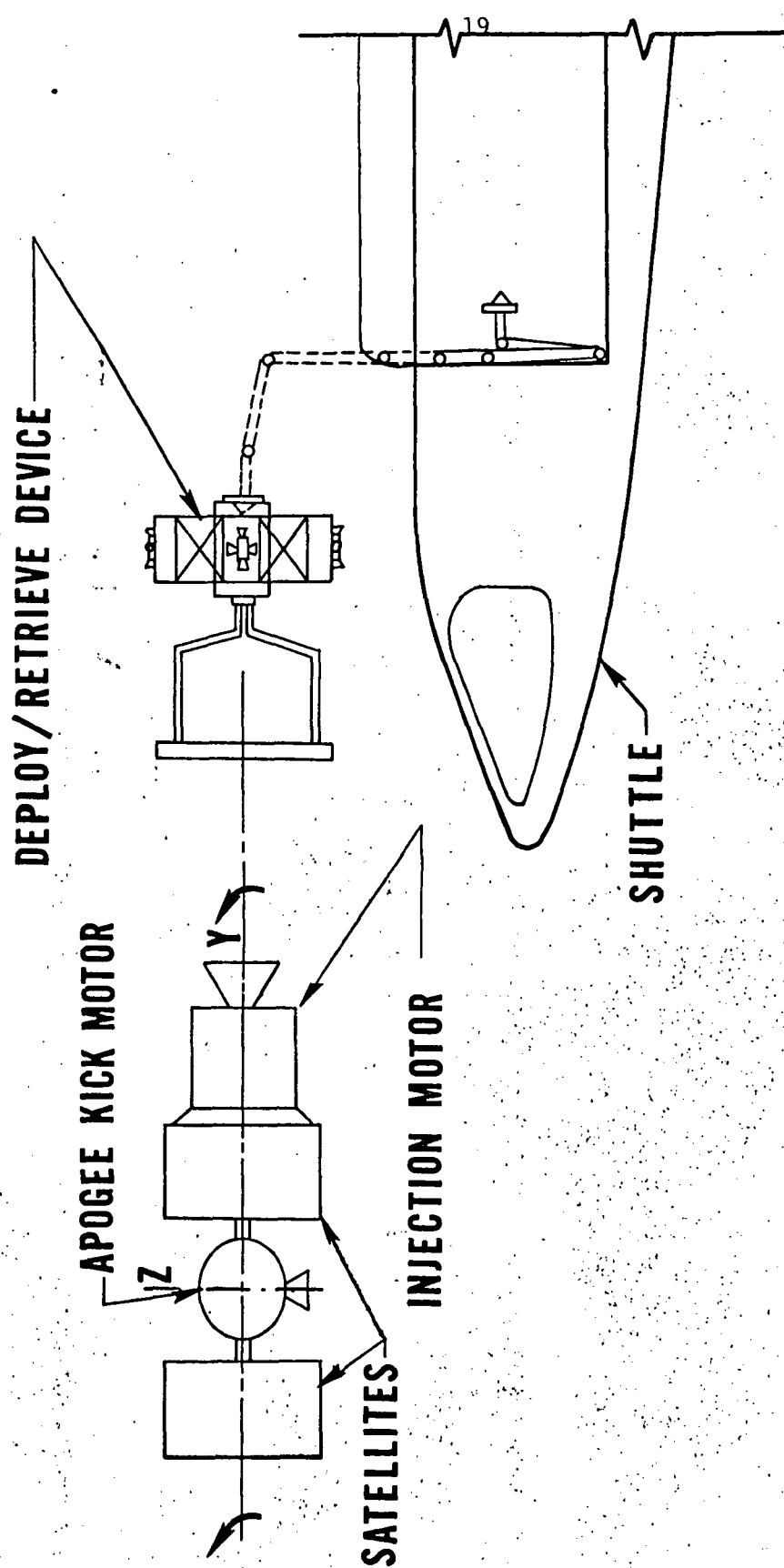
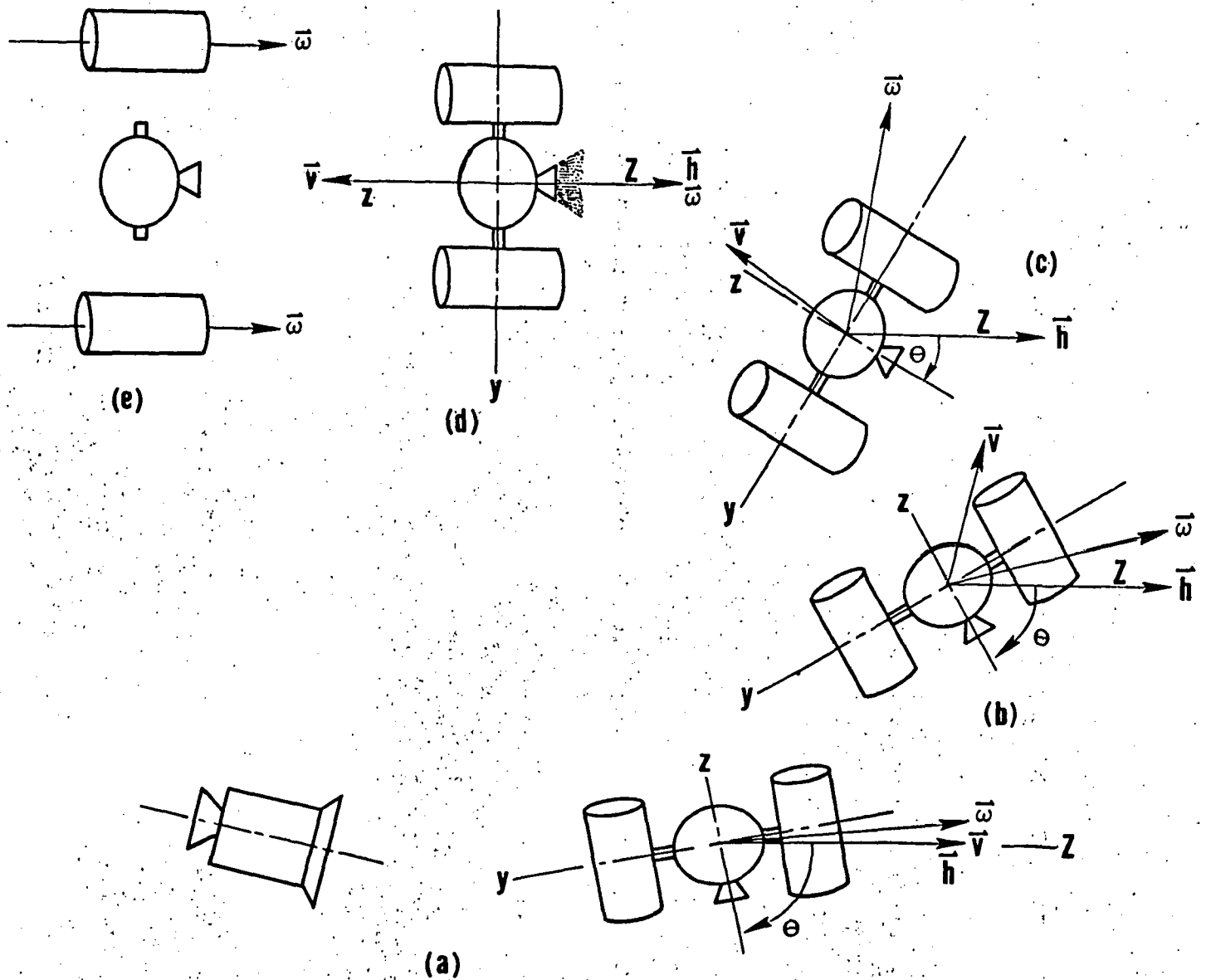Figure 7. AMAPS Package Leaving Deploy/Retrieve Device

Figure 8. Deployment Sequence for Shuttle Scheme.

3. PUBLICATIONS AND RESEARCH REPORTS RESULTING FROM THIS STUDY

1. _____, "First Semi-Annual Progress Report on Problems Related to Retrieval of Uncooperative Orbiting Objects," NASA Grant NGR 39-009-162, July 1970.

2. Kaplan, M. H., "Review of Classified Material Relevant to Orbital Retrieval of Uncooperative Objects," Final Report for Contract W13, 218, December 17, 1970. This also appears as Appendix A in the Second Semi-Annual Progress Report, January 1971.

3. _____, "Second Semi-Annual Progress Report on Problems Related to Retrieval of Uncooperative Orbiting Objects," NASA Grant NGR 39-009-162, January 1971.

4. Kaplan, M. H., Yarber, W. H., Creehan, E. F., and Thoms, E. C., "Dynamics and Control for Orbital Retrieval Operations Using the Space Shuttle," presented at the AIAA Space Shuttle Development Testing and Operations Conference/NASA Shuttle Technology Conference, March 1971. Also published in NASA-KSC TR-1113, Vol. 1, May 1971, pp. 175-201.

5. Yarber, W. H., "Conceptual Design, Dynamics and Control of a Device for Despinning Orbiting Objects," M.S. Thesis, The Pennsylvania State University, June 1971. Also published as Astronautics Research Report No. 71-2, Department of Aerospace Engineering, The Pennsylvania State University, May 1971.

6. _____, "Third Semi-Annual Progress Report on Problems Related to Retrieval of Uncooperative Orbiting Objects," NASA Grant NGR 39-009-162, July 1971.

7. Kaplan, M. H., "The Problem of Docking with a Passive Orbiting Object Which Possesses Angular Momentum," abstract accepted to the 22nd Congress of the International Astronautical Federation, Brussels, September 1971. Also appearing in Astronautical Research 1971, proceedings of the 22nd I.A.F. Congress.

8. Beck, N. M., "Attitude Dynamics and Control of an Apogee Motor Assembly with Paried Satellites," M.S. Thesis, The Pennsylvania State University, September 1971.

9. _____, "Fourth Semi-Annual Progress Report on Problems Related to Retrieval of Uncooperative Orbiting Objects," NASA Grant NGR 39-009-162, January 1972.

10. Kaplan, M. H., and Beck, N. M., "Attitude Dynamics and Control of an Apogee Motor Assembly with Paried Satellites," AIAA Paper No. 71-953, presented at the Guidance, Control and Flight Mechanics Conference, Hofstra University, Hempstead, N. Y., August 1971. Also published in the Journal of Spacecraft and Rockets, Vol. 9, No. 6, June 1972, pp. 410-415.

11. _____, "Fifth Semi-Annual Progress Report on Investigation of Technical Problems Related to Deployment and Retrieval of Spinning Satellites," NASA Grant 39-009-162, July 1972.

12. Cenker, R. J., "Spin Reorientation of a Nonsymmetrical Body with Energy Dissipation," M.S. Thesis, The Pennsylvania State University, March 1973. Also published as Astronautics Research Report No. 73-2, Department of Aerospace Engineering, The Pennsylvania State University, March 1973.

4. FOLLOW-ON RESEARCH STUDIES

Further investigations based on work performed in the completed grant would consider several technical questions related to retrieval and deployment using teleoperators in connection with the space shuttle system. Activities should be closely coordinated with current NASA objectives. Specific areas to be included in such a study are outlined below.

The eventual state of a passive satellite to be retrieved depends on its initial passive attitude motion, internal energy dissipation, and outside perturbing torques arising from solar pressure, drag, etc. Initial attitude motion may be the result of attitude jet or wheel failures. Specific satellites would be considered and realistic failure modes assumed in order to develop general requirements for retrieval system designs. Energy dissipation can also be anticipated, permitting determination of eventual attitude motion through energy considerations and computer simulation.

A considerable amount of work on control system synthesis for various operational modes of the retrieval sequence has already been done. However, results were limited to somewhat simplified cases. Such techniques would be used with configurations being considered by NASA to aid in end effector design, define limits on capture situations, and aid in generating future interface requirements for satellites to be retrieved.

A balance of automatic and remote control functions must be sought
to insure successful teleoperator maneuvers under a variety of circumstances.
Generally, attitude control is assumed automatic except in the final
alignment phase during capture operations. Position control has been
assumed to be manual. However, more definitive divisions should be
made, based on retrieval or deployment situations expected.

One area of particular interest is simulation of spin-up processes
with a variety of inertia properties and control system characteristics.
Results should lead to practical limits on the uses of free-flying and
attached deployment and retrieval devices.

These technologies will be very useful in making decisions concerning
shuttle applications and the orbit-to-orbit tug design.